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Solar drying of agricultural products: A review

A.A. El-Sebaii[a,*], S.M. Shalaby[b]

[a] Department of Physics, Faculty of Science, King Abdulaziz University, P.O. Box 80203, Jeddah 21589, Saudi Arabia
[b] Department of Engineering Physics and Mathematics, Faculty of Engineering, Tanta University, Tanta 31111, Egypt

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ABSTRACT

The use of solar energy in recent years had reached a remarkable edge. The continuous research for an alternative power source due to the perceived scarcity of fuel fossils is its driving force. It had become even more popular as the cost of fossil fuel continues to rise. Of all the renewable sources of energy available, solar energy is the most abundant one and is available in both direct as well as indirect forms. Solar energy applications were divided mainly into two categories: the first is the direct conversion to electricity using solar cells (electrical applications). The second is the thermal applications. The latter include solar heating, solar cooling, solar drying, solar cooking, solar ponds, solar distillation, solar furnaces, solar-thermal power generation, solar water heating, solar air heating, etc. Detailed description, fundamentals and previous work performed on solar dryers and solar air heaters, as the vital element for the indirect and mixed modes of solar dryers, were presented in the present review paper.

Contents

1. Introduction

Drying is defined as a process of moisture removal due to simultaneous heat and mass transfer. It is a classical method of food preservation, which provides longer shelf-lighter weight for transportation and small space for storage [1]. The drying process takes place in two stages. The first stage happens at the surface of the drying material at constant drying rate and is similar to the vaporization of water into the ambient. The second stage takes place with decreasing (falling) drying rate. The condition of the second stage determined by the properties of the material being dried [2]. Open sun drying is the most commonly used method to preserve agricultural products like grains, fruits and vegetables in most developing countries. Such drying under hostile climate conditions leads to severe losses in the quantity and quality of the dried product [3]. These losses related to contamination by dirt, dust and infestation by insects, rodents and animals. Therefore, the introduction of solar dryers in developing countries can reduce crop losses and improve the quality of the dried product significantly when compared to the traditional methods of drying such as sun or shade drying [4]. Solar drying methods are usually classified to four categories according to the mechanism by which the energy, used to remove moisture, is transferred to the product [5]:

(1) *Sun or natural dryers*: The material to be dried is placed directly under hostile climate conditions like solar radiation, ambient air temperature, relative humidity and wind speed to achieve drying.
(2) *Direct solar dryers*: In these dryers, the material to be dried is placed in an enclosure, with transparent covers or side panels. Heat is generated by absorption of solar radiation on the product itself as well as the internal surfaces of the drying chamber.

* Corresponding author. Permanent address: Department of Physics, Faculty of Science, Tanta University, Tanta, Egypt. Tel.: +966 505604537; fax: +966 26951106.
E-mail address: aasebaii@yahoo.com (A.A. El-Sebaii).

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This heat evaporates the moisture from the drying product and promotes the natural circulation of drying air.

(3) *Indirect solar dryers*: In these dryers, air is first heated in a solar air heater and then ducted to the drying chamber.

(4) *Mixed-type solar dryers*: The combined action of the solar radiation incident directly on the material to be dried and the air pre-heated in the solar air heater furnishes the energy required for the drying process.

2. Previous work on solar dryers

2.1. Direct solar dryers

Drying of agricultural and marine products is one of the most attractive and cost-effective application of solar energy. Numerous types of solar dryers had been designed and developed in various parts of the world, yielding varying degrees of technical performance. The simplest of solar cabinet dryer was reported by Fudholi et al. [6], it was very simple, and consists essentially of a small wooden hot box. Dimensions of this dryer was 2 m × 1 m where the sides and bottom were constructed from wood and metal sheets. A transparent polyethylene sheet was used as cover at the upper surface. Air holes were located on the sides of the dryer for circulation. Evaluation performance studies of solar cabinet dryers were reported by many investigators [7–9]. Sharma et al. [9] found that the predicted plate temperature for no load reaches a maximum of 80–85 °C during the noon hours, while with a load of 20 kg of wheat, the maximum temperature was 45–50 °C. Gbaha et al. [10] designed and tested experimentally a direct type natural convection solar dryer for drying cassava, bananas and mango slices. This dryer is a simple design and can be manufactured by farmers from local materials. It has a relatively moderate cost and is easy to use. The thermal performance of the newly developed dryer was found to be higher compared to open sun drying for the selected food materials. Singh et al. [11] investigated a small size domestic natural convection solar dryer. It is mainly consists of a hot box, base frame, trays and shading plates. A transparent window glass (4 mm thick) was fixed as glazing. It was fixed to the hot box with an aluminum angle. In order to provide air circulation in the dryer, 40 holes with total area of 0.002 m^2 were drilled in the top and sides of the dryer. A flat sheet of 5 cm thick of thermocole was used as insulator. Mursalim et al. [12] evaluated a modified cabinet dryer with natural convection system. The dryer had a single transparent plastic cover and the sawdust was used as an insulating material. The drying chambers walls were build of plywood painted black with dimensions 120 cm × 80 cm × 40 cm (long, width, and height). For air flow, 12 holes were provided at the bottom.

2.2. Indirect solar dryers

The main disadvantages of the cabinet or direct solar dryers are: (i) small capacity of the crop; hence, they cannot used for commercial purposes, (ii) the required drying time is long, (iii) due to evaporation of moisture and its condensation on the glass cover, the transmissivity of the glass cover is reduced, (iv) overheating of the crop may take place due to direct exposure to sunlight; consequently, the quality of the product may deteriorate, and (v) the efficiency is low because part of the solar energy input is used to induce air flow, and the product itself acts as an absorber. In order to solve the above problems, various design of indirect solar dryer had been developed and tested. These designs had been recommended for commercial purposes. The indirect type solar dryers include the chamber-type dryers (tray and rack type dryer, bin type, and tunnel type), chimney-type dryers and wind-ventilated dryers.

Bolaji [13] investigated an indirect solar dryer using a box type absorber collector. The dryer consists of an air heater, an opaque crop bin, and a chimney. The box-type absorber collector, made of a glass cover and black absorber plate, was inclined at angle of 20° to the horizontal to allow the heated air to rise up the unit with little resistance. He reported that the maximum efficiency obtained in the box-type absorber system was 60.5%. He found also that the maximum average temperatures inside the collector and drying chamber were 64 and 57 °C, respectively; while, the maximum observed ambient temperature was 33.5 °C. Madhlopa et al. [14] developed a solar dryer which had composite absorber systems on the principles of psychometry. The dryer consists of a flat plate collector, wire mesh absorber, glass cover, chimney and drying chamber. The heater was integrated to a drying chamber for food dehydration. The performance of the dryer was evaluated by drying fresh samples of mango. Results showed that the temperature rise of the drying air was up to 40 °C during noon hours. The thermal efficiency of the flat plate collector and wire mesh absorber were approximately 17% and 21%, respectively, at flow rate 0.0083 kg/s. Pangavhane et al. [3] designed and developed a multipurpose natural convection indirect solar dryer consisting of a solar air heater and drying chamber. The solar air heater consists of a finned absorber (painted matte black), glass cover, insulation and frame. The air duct beneath the absorber was made from an aluminum sheet through which air was passed. The U-shaped corrugations (11 in number) were placed in the absorber plate parallel to the direction of airflow. Aluminum fins (a matrix foil 0.15 mm thick) were fitted to the back of the absorber. At the lower end of the collector (air inlet), shutter Plates 4 mm thick and 0.08 m × 0.4 m in size, were also provided to stop the air flowing during the night. The air duct was made leak-proof with a good quality sealing material. The entire unit was placed in a rectangular box made from a galvanized iron sheet of 0.9 mm thick. The gap between the bottom of the air duct and the box was filled with glass wool insulation. This system can be used for drying various agricultural products like fruits and vegetables. Grapes were successfully dried in this solar dryer. Sharma et al. [15] investigated a multistacked natural convection solar dryer. It is a simple solar dryer housed in a single cubic wooden box. The box had been divided into two halves. The first half is a single glazed solar air collector, whereas the drying unit is in the second half of the complete unit. A glazed solar air heater located at the base of the drying chamber provides supplementary heat. Preheated air in the solar collector rises through the second half of the system. A chimney was provided at the top of the drying unit. The hot air dehydrates the product and gets exhausted through the chimney. The dried product was placed on the moveable trays kept on the metallic frames. The system can be operated both in natural as well as in forced convection mode.

The indirect-mode forced convection solar dryer essentially consists of an air heater, drying chamber, and a blower/fan to duct the heated air into the drying chamber. Al-Juamily et al. [16] constructed and tested an indirect-mode forced convection dryer for drying fruits and vegetables in Iraq. The solar dryer consists of a solar collector, a blower, and a solar drying cabinet. Two identical air solar collectors having V-groove absorption plates of two air passes and a single glass cover were used. The total area of the collectors was 2.4 m^2. The dimensions of the drying cabinet were 1 m × 0.33 m × 2 m (width, depth, and height). The cabinet was divided into six divisions separated by five shelves. The distance between the shelves was 0.3 m except the upper one, which was 0.5 m from the roof. Each shelf had dimensions of 0.95 m × 0.3 m and was made of a metallic mesh. Two types of fruits and one type of vegetables were dried during this dryer. These were grapes, apricots, and beans. The moisture content of apricot had been reduced from 80% to 13% within one day and a half of drying. Moreover, the moisture content of grapes had been reduced from 80% to 18% in

two and a half days of drying. Finally, the beans moisture content had been reduced from 65% to 18% in 1 day only. They concluded that the air temperature is the most effective factor on drying rate. The effect of variation of the speed of air inside the drying cabinet was small and may be neglected. They also concluded that the relative humidity of air exits from the cabinet was small (between 25% and 30%) and therefore there is no need for high velocity of air inside the cabinet. Solar drying system using V-groove solar collector was also developed and tested by Kadam and Samuel [17] for drying cauliflower. Cauliflower was blanched for 3 min in boiling water and dipped in sodium chloride, potassium metabisulphite and sodium benzoate for 15 min in 1% preservative concentration level before drying cauliflower in solar dryer. The treatment was found to be significantly different for all preservatives. They concluded that the potassium metabisulphite was the best among sodium chloride and sodium benzoate. Karim and Hawlader [18] studied the V-groove, fins and flat-plate collectors for crop drying applications. The results showed that the V-groove collector had 7–12% higher efficiency than flat-plate collector. The double pass operation of the collector improved the efficiency of all three collectors. The efficiency of all the air collectors is a strong function of airflow rate. The flow rate 0.035 (kg/m^2 s) was considered optimal for solar drying of agricultural product. Karsli [19] investigated the thermal performance of four types of air heating flat plate solar collectors for drying application: a finned collector with an angle of 75°, a finned collector with an angle of 70°, a collector with tubes and a base collector. Banout et al. [20] introduced a new design of double-pass solar dryer (DPSD). They compared the performances of the DPSD with those of a typical cabinet dryer (CD) and a traditional open-air sun drying for drying of red chilli. The energy and exergy analyses of the thin layer drying process of mulberry via forced solar dryer were studied by Akbulut and Durmus [21]. El-Beltagi et al. [22] developed a mathematical model of a thin layer drying for strawberry using an indirect forced convection solar dryer. The dryer consisted of a drying chamber, and a solar collector with W-corrugated black aluminum sheet to absorb most of the available solar radiation. Heat dissipation by convection was minimized by placing a flat transparent glass cover 4 mm thick on the top of the corrugated sheet. The solar collector was tilted at an angle of 20° from the horizontal plane. Ambient air was drawn in by a fan and heated up in the solar collector then enters the drying chamber through the bottom and up through the samples and through the chimney. Dissa et al. [23] introduced mathematical model and experimental validation of thin layer indirect solar drying of mango slices. Goyal and Tiwari [24,25] developed and analyzed a model using both a reverse flat-plate absorber as the heating medium and a cabinet dryer as the drying chamber. The whole unit was termed as a reverse absorber cabinet dryer (RACD). The absorber plate was horizontal and downward facing. A cylindrical reflector was placed under the absorber to introduce solar radiation from below. The area of the aperture was the same as that of the absorber plate. The cabinet dryer was mounted on the top of the absorber maintaining a gap of 0.03 m for air to flow above the absorber plate. The incoming air was heated and entered the dryer from the bottom. The bottom area of the dryer was equal to that of the absorber plate area. The inclination of the glass cover was taken as 45° from horizontal to receive maximum radiation. The thermal performance of the new proposed dryer was analyzed by solving the various energy balance equations using the finite difference technique. Mohanraj and Chandrasekar [26] were design, fabricated and tested an indirect-mode forced dryer for drying copra. The moisture content of copra reduced from 51.8% to 7.8% and 9.7% in 82 h for trays at the bottom and top, respectively. Sarsilmaz et al. [27] conducted experiments on drying of apricots in a newly developed rotary column cylindrical dryer (RCCD) equipped with a specially designed air solar collector to find the optimum drying air rate and rotation speed of dryer, to maintain uniform and hygienic drying conditions and to reduce drying times. The systems were constituted of three parts: air blow region (fan), air heater region (solar collector) and drying region (rotary chamber).

2.3. Solar dryers with heat storage media

Several workers have explored different techniques for accelerating the solar drying of various agricultural products by considering the possible use of thermal storage materials, and developed drying models to predict the drying curves of the dried materials [28–33]. A review article of the solar drying systems incorporating with phase change materials (PCM) for drying agricultural food products was recently presented by Bal et al. [33]. Tiwari et al. [28,29] experimentally evaluated a crop dryer-cum-water heater and crop dryer rock bed storage. They reported that the energy balance equations for each component of the system have been used to predict the analytical results. On the basis of the analytical results, it was observed that the drying time is significantly reduced on using the water and the rock best as storage media. The system can be used to provide hot water in case the drying system is not in operation. The water heater below the air heater systems will act as a storage material for drying the crop during off-sunshine hour. Comparative performance of coriander dryer coupled to solar air heater and solar air heater-cum rock bed storage was studied by Chauhan et al. [30]. They concluded that the average moisture content of the grains in the grain bed can be reduced from 28.2% (db) to 11.4% (db) in 27 cumulative sunshine hours (i.e. 3 sunshine days) by using the solar air heater only; whereas, by using the solar air heater during sunshine hours and the rock bed energy storage during off-sunshine hours the same amount of moisture can be evaporated in 31 cumulative hours (18 sunshine and 13 off sunshine hours). During sunshine drying, the effect of grain bed depths on drying performance of coriander was observed to be remarkable, while the air mass velocity has no significant effect on the moisture content reduction rate. However, off-sunshine drying time can be reduced by 1 h for each increment of 50 ($kg/h\,m^2$) in air mass velocity. Hence, the heat stored in the rock bed can be used effectively for heating the inlet (ambient) air for off-sunshine drying of agricultural products. Jain and Jain [31] and Jain [32] modeled the system performance of multi-tray crop drying using an inclined multi-pass solar air heater with built-in thermal storage. They concluded that the proposed mathematical model is useful for evaluating the thermal performance of a flat plate solar air heater for the crop drying in multiple trays. It is also useful for predicting the moisture content, crop temperature and drying rate in the different drying trays. They also concluded that the grain temperature increase with the increase of collector length, breadth and tilt angle up to typical value of these parameters. El-Sebaii et al. [34] designed an indirect type natural convection solar dryer. It consists of a flat-plate solar air heater connected to a cabinet acting as a drying chamber. Sand was used as the thermal storage material. The drying parameters such as drying temperature, ambient temperature, relative humidity, solar irradiance and temperature distribution in different parts of the system during drying had been recorded. Grapes, figs, apples, green peas, tomatoes and onions were dried successfully with and without using the storage material. They concluded that the equilibrium moisture content M_e for seedless grapes was reached after 60 and 72 h when the system was used with and without storage the material, respectively. Therefore, the storage material reduced the drying time by 12 h. In order to accelerate the drying process, the drying products are divided into pieces and then chemically treated by dipping the samples into boiling water containing 0.4% olive oil and 0.3% NaOH for 60 s. The required time to achieve M_e for the chemically treated seedless grapes, when the system is used with sand as a storage material, was drastically reduced to 8 h.

Moreover, they found that the storage and chemical pretreatment have caused significant decreases of the drying time for all the investigated crops. Enibe [35] designed and evaluated a passive solar powered air heating system, for the crop drying and poultry egg incubation, consisting of a single-glazed flat-plate solar collector integrated with a PCM as a heat storage material. The PCM was prepared in modules, with the modules equispaced across the absorber plate. The spaces between the module pairs serve as the air heating channels, the channels being connected to common air inlet and discharge headers. The system was tested experimentally under daytime no-load conditions, over the ambient temperature range of 19–41 °C, and a daily global irradiation range of 4.9–19.9 MJ/m^2. These results showed that the system can be operated successfully for crop drying applications. Shanmugam and Natarajam [36] fabricated an indirect forced convection with desiccant integrated solar dryer. The main parts were: a flat-plate solar air collector, a drying chamber, desiccant bed and a centrifugal blower. The system was operated in two modes, sunshine hours and off sunshine hours. During sunshine hours, the hot air from the flat plate collector was forced to the drying chamber for drying the product and simultaneously the desiccant bed receives solar radiation directly and through the reflecting mirror. During off sunshine hours, the dryer was operated by circulating the air inside the drying chamber through the desiccant bed by a reversible fan. The dryer was used to dry 20 kg of green peas and pineapple slices. Drying experiments were conducted with and without the integration of desiccant unit. The effect of using a reflecting mirror on the drying potential of the desiccant unit was also investigated. With the inclusion of reflecting mirror, the drying potential of the desiccant material was increased by 20%. Approximately, in all the drying experiments 60% of moisture was removed by the air heated using solar energy and the remainder by the desiccant. The inclusion of reflecting mirror on the desiccant bed caused faster regeneration of the desiccant material.

2.4. Mixed-type solar dryers

In this type of solar dryers the material to be dried is heated by two ways, through the direct absorption of solar radiation and the preheated air coming from the solar air heater. Bolaji and Olalusi [37] constructed a mixed-mode solar dryer for food preservation. They reported that the temperature rise inside the drying cabinet was up to 74% for about 3 h immediately after 12.00 h (noon). The drying rate and system efficiency were 0.62 kg/h and 57.5%, respectively. The rapid rate of drying in the dryer reveals its ability to dry food items reasonably rapidly to a safe moisture level. Results showed also that during the test period, the temperatures inside the dryer and solar collector were much higher than ambient temperature during most hours of the day-light. Tripathy and Kumar [38] constructed a laboratory scale mixed-mode solar dryer consisting of an inclined flat plate solar collector connected in series to a drying chamber glazed at the top. They used the dryer to perform natural convection drying of potato cylinders of length 0.05 m and diameter 0.01 m and slices of diameter 0.05 m and thickness 0.01 m. Simate [39] designed, constructed and tested two different types of natural convection solar dryers. For the mixed-mode, the drying chamber cover was transparent whereas for the indirect mode it was opaque. Numerical calculations indicated that a shorter collector length should be used for the mixed-mode solar dryer (1.8 m) compared to the indirect-mode dryer (3.34 m) of the same capacity (90 kg). The quantity of dry grain obtained from the mixed-mode for the whole year is about 2.81 tones and was less than that from the indirect mode by 15%. Forson et al. [40] designed a mixed-mode natural convection solar dryer. They proposed a methodology combining principles/concepts and rules of thumb that enable the design of a properly engineered mixed-mode natural convection solar crop dryer. The resulting empirical model requires the crop physical properties and the location ambient conditions as input data. Singh et al. [41] developed a natural convection solar dryer. The dryer had a multi-shelf-design with intermediate heating, passive, integral, direct/indirect and portable solar dryer. It had four main components, multi-tray rack, movable glazing, shading plate and trays. The multi-rack was inclined depending upon the latitude of the location. The movable glazing consisted of a movable frame and a stabilized plastics sheet. It was fixed on the movable frame. The dryer could be used in cottage industries in remote places due to its low cost.

Numerous research works relating the mathematical modeling and kinetics of the drying process of agricultural products for describing the thin layer drying characteristics, such as those concerning mint [42,43], figs [34,44,45], grapes [3,16,36], strawberry [14], banana [46,47], pineapples [48], mango [10,14,23], potatoes and apples [49], red peppers [50], eggplants [10], green peas [32,34], okra [51], green beans [16,52], apricot [16], red chilli [20], mulberry [21], prickly pear cactus cladodes [53], cauliflowers [17], pistachio [54], black tea [55], olive pomace [56].

3. Previous work on solar air heaters

To improve the thermal performance of the indirect solar dryers, the thermal performance of the solar air heater connected to the drying chamber should be improved. The next sections review the methods that were used to improve the thermal performance of the solar air heaters.

Several designs for solar air heaters had been proposed and discussed in the literature. The designer and potential user of these systems must consider a number of factors when comparing their merits. These can mainly be categorized as: (i) thermal performance, (ii) cost and (iii) lifetime, durability, maintenance and ease of installation. Thermal performance of collectors was compared by using the concept of thermal efficiency. It was generally believed that the thermal efficiency of a solar air heater is the major requirement for the prediction of thermal performance of the complete solar system of which the solar air heater is a part [57]. Ekechukwu and Norton [58] classified the solar air heaters broadly into two types: bare plate and cover plate solar air heaters. The bare plate solar air heater consists of a single channel design with single air flow between absorber and bottom plates with insulation. Choudhury et al. [59] studied the thermal performance of this design. The thermal performance of this air heater had been also predicted by Ong [60]. Njomo [61] and Njomo and Daguenet [62] investigated heat transfer in this design.

In the cover plate solar air heaters the heater was covered by a single or double glass covers. The single cover solar air heater in which the air flow in a single channel between the cover and absorber plate was investigated by [60,62–68]. Hegazy [69] investigated the effect of variation in the absorber width on both the thermal and hydraulic performances of the single cover solar air heater. Aboul-Enein et al. [70] analyzed a flat plate solar air heater with and without thermal storage material under the absorber plate. The single duct double glass solar air heaters with air flowing between the lower glass cover and the absorber plate had been studied by Njomo and Daguenet [62], Mohamad [65] and Naphon and Kongtragool [67]. Mohamad [65] investigated the heat transfer in this design under the steady state conditions.

In the back-pass solar air heater, the absorber plate was placed directly behind the transparent cover with a layer of static air separating it from the cover. The air to be heated flows between the inner surface of the absorber plate and the layer of insulation [58].

The heat transfer in this design had been investigated by Choudhury et al. [59], Ong [60], Garg et al. [71], Choudhury et al. [72], Al-Kamil and Al-Ghareeb [73], Jannot and Coulibaly [74] and Hegazy [69,75].

The double-pass solar air heater consists of one glass cover, double channels in which the air flows between the glass cover and the absorber plate (upper channel) and between the absorber and bottom plates (lower channel) with an insulation behind the back plate. The double-pass solar air heater was investigated by many authors [60,66,67,69,76,77]. Yeh et al. [78] investigated the heat transfer of the double-pass solar air heater with the presence of second glass cover. The double-pass double glass cover solar air heater with the air firstly flows in the upper channel and then forced to circulate to the lower channel was presented by Choudhury et al. [72], Yeh et al. [79] and Ho et al. [80]. They found that, increasing the velocity of air enhances the heat transfer coefficient, resulting in improved performance. In addition to increasing the fluid velocity, the recycling of air also produces the effect of remixing the inlet fluid with the hot outgoing fluid. Naphon [81] studied theoretically the heat transfer characteristics and performance of a double-pass flat solar air heater with recycle with and without porous media.

The single pass solar air heater with single and double glass covers with the passage filled with packing was studied by Choudhury and Garg [82]. Ramadan et al. [83] investigated the double-pass solar air heater with packed bed in which; the air was firstly forced through the packed bed existing in the upper channel formed between the lower cover and the absorber plate, and was then re-circulated to flow in the opposite direction through the lower channel, formed between the absorber and back plates. The different heat transfer mechanisms in terms of the various heat transfer coefficients were also studied. El-Sebaii et al. [84] proposed an investigation of heat transfer on a double-pass solar air heater where the air was firstly forced through the upper channel, formed between the lower cover and the absorber plate, and then re-circulated to flow in the opposite direction through the packed bed that exists in the lower channel, formed between the absorber and back plates. The thermal performances of single and double pass solar air heaters with steel wire mesh layers instead of the flat absorber plate were experimentally investigated by Aldabbagh et al. [85]. Comparisons between the performances of a packed bed collector with those of a conventional collector showed a substantial enhancement in the thermal efficiency.

Ho et al. [86] developed a theoretical formulation of the energy balance equations for a multi-pass solar air heater with external recycle and investigated the recycle effect on collector efficiency. The effect of channel depth ratio on the collector efficiency was also studied. Jain and Jain [31] and Jain [32] investigated the heat transfer mechanisms in the multi-pass solar air heater with build-in thermal storage. In this model, the solar radiation transmits from the glass covers and is absorbed by the absorber plate. The air flows in between the covers, above the absorber plate and below the storage material, where it is heated along the path. The porous or matrix type solar air heater consists of single glazing at the top, matrix, back metallic plate and insulation. In a design, the air flows upward through the matrix and in other design; it flows downward through the matrix. These models had been investigated by Sharma et al. [87,88].

Due to the poor thermal conductivity and small heat capacity of air, the convective heat transfer rate inside the air flow channel where the air is heated is low. Big efforts had been made to increase this rate. One of the effective ways to increase the convective heat transfer rate is to increase the heat transfer area or to increase turbulence inside the flowing channel by using fins or corrugated surface [89–93]. El-Sebaii et al. [94,95] performed theoretical and experimental investigations of forced convection double pass v-corrugated [94] and finned [95] solar air heaters and compared their performances with those for a double pass flat plat solar air heater. They were concluded that the double pass v-corrugated plate solar air heater is 9.3–11.9% and 11–14% more efficient than the double pass finned plate solar air heater [95] and the conventional double pass flat plate solar air heater [94], respectively. Performance evaluation of a natural convection solar air heater with a rectangular finned absorber plate was conducted by Pakdaman et al. [96]. It was indicted that the main parameter which characterizes the thermal behavior of the system is the solar radiation. Besides, exergy analysis had been carried out and the optimum conditions that achieved the highest performance had been determined. The influence of recycle on the performance of baffled double-pass flat-plate solar air heaters with internal fins attached was performed by Ho et al. [97]. Alta et al. [98] investigated experimentally three different types of solar air heaters; two having fins and the other without fins. One of the heaters with fins had single glass cover and the others had double glass covers. Based on the energy and exergy output rates they concluded that, the heater with double glass covers and fins was more effective and the difference between the input and output air temperature was higher than the others. The performance of single and double pass solar air heaters with fins and steel wire mesh as absorber was investigated experimentally by Omojaro and Aldabbagh [99]. They found that, the efficiency increase with increasing air mass flow rate and for the same mass flow rate, the efficiency of the double pass was found to be higher than the single pass by 7–9%. Karim and Hawlader [100] studied the thermal performance of flat plate, v-corrugated and finned air collectors. They indicated that, the V-groove collector is the most efficient collector and the flat-plate collector is the least efficient one. Optimum conditions of these three collectors were studied to perform up to approximately 70% thermally efficiency at 0.031 (kg/m^2 s) could be attained with the V-groove. Nwosu [101] investigated the pin fins attached to the absorber of a solar air heater. A comparison between flat plate, V-grooved and chevron pattern absorbers was presented by El-Sawi et al. [102]. They concluded that, under the considered configurations and operating conditions, the chevron pattern absorber was found to be the most efficient and the flat plate one was the least efficient. The chevron pattern was found to have higher performance, reaching up to 20% improvement in thermal efficiency and an increase of 10 °C in outlet temperature at some ranges of mass flow rates. Performance analysis of a new flat-plate solar air heater with several obstacles at different angles and without obstacles was experimentally studied by Akpinar and Kocyigit [103]. They found that the efficiency of the solar air collectors depends significantly on the solar radiation, surface geometry of the collectors and the extension of the air flow line. They concluded also that, the largest irreversibility was occurring at the solar air heater without obstacles for which the collector efficiency was smallest. A computational analysis of heat transfer augmentation and flow characteristic due to rib roughness over the absorber plate of solar air heaters were presented by Chaube et al. [104]. Sahu and Bhagoria [105] investigated experimentally the heat transfer coefficient by using 90° broken transverse ribs on the absorber plate of a solar air heater. They concluded that the roughened absorber plates increase the heat transfer coefficient 1.25–1.4 times as compared to smooth rectangular duct under similar operating conditions at higher Reynolds number. The heat transfer and friction characteristics of rectangular solar air heater duct using rib-grooved artificial roughness was studied by Jaurker et al. [106]. They inferred that as comparison to the smooth duct, the presence of rib-grooved artificial roughness yields Nusselt number up to 2.7 times while the friction factor rises up to 3.6 times in the range of the parameters investigated. The performance of solar air heaters having v-down discrete rib roughness on the absorber plate was investigated by Karwa and Chauhan [107]. Analysis of fluid flow and heat transfer in a rib grit roughened surface solar air heater was presented

by Karmare and Tikekar [108]. The previous studies on rib roughness over the absorber plate of the solar air heaters indicated that the artificial roughness results in the desirable increase in the heat transfer rate with the penalty of the undesirable increase in the pressure drop due to the increased friction.

4. Conclusions and recommendations for future work

One of the most important potential applications of solar energy is the solar drying of agricultural products. Losses of fruits and vegetables during their drying in developing countries are estimated to be 30–40% of production. The postharvest losses of agricultural products in the rural areas of the developing countries can be reduced drastically by using well-designed solar drying systems. Among the different types of solar dryers, the indirect mode forced convection solar dryer has been demonstrate to be superior in the speed and quality of drying. Since the solar air heater is the most important component of the indirect solar drying system, improvement of the solar air heater would led to better performance of the drying system. Therefore; more studies to investigate and improve the thermal performance of double pass flat, v-corrugated and finned plate solar air heaters is still of considerable interest. Incorporating of sensible and/or latent heat storage media within the solar drying systems accelerate the drying process during the night time and low intensity solar radiation periods and exclude the need for using auxiliary heat sources during low solar radiation seasons. The latent storage media is preferable compared to the sensible store media to achieve nearly constant drying air temperature during the drying process. However, the phase change materials should be investigated in view of their chemical stability and compatibility with the containing materials before their integration within the drying system. Furthermore, before using the drying systems on large scale, computer simulation models must be performed to simulate the short and long terms performance of the drying systems with and without the storage media to estimate the solar drying curves of the dried products and investigate the cost benefits of the solar drying of agricultural products.

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